Lepton flavor violation of tau decays at Belle/Belle II

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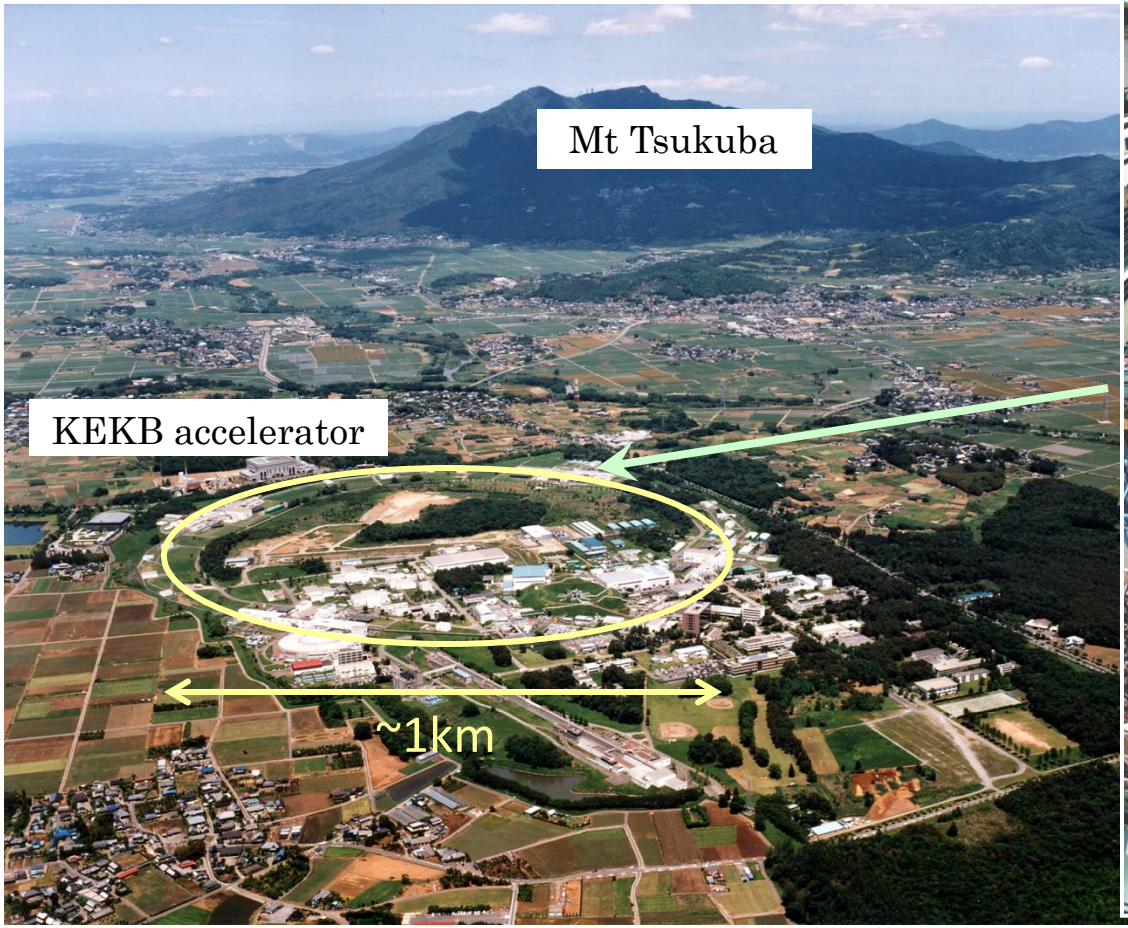
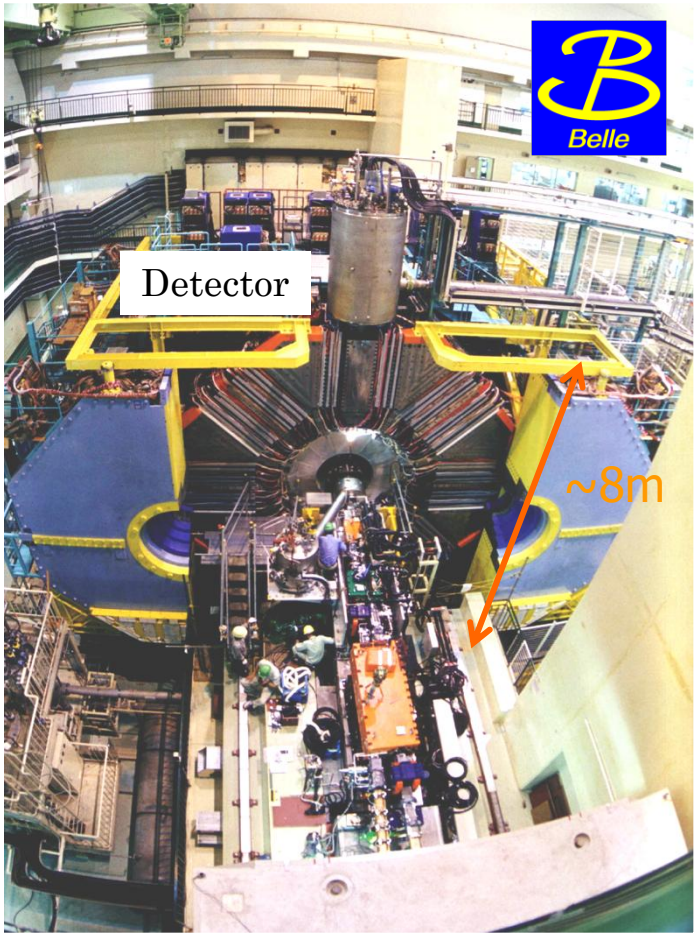
For Belle and Belle II collaboration

KEKB/Belle experiment

- Electron(8GeV)-positron(3.5GeV) collider experiment at KEK Tsukuba Japan
- A B-factory is also a tau-factory. Collected ~10^9 τ pairs
- Belle detector; good tracking and particle identification, forward/backward asymmetric geometry.



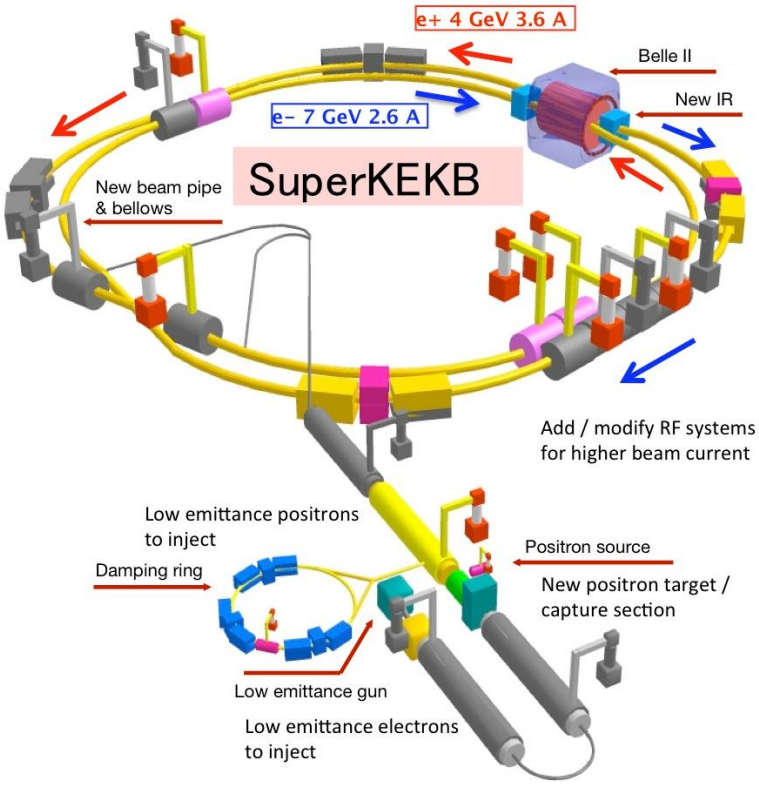


SuperKEKB and Belle II experiment

- Advanced B-factory
  - Electron (7GeV), positron (4 GeV)
- Upgraded KEKB accelerator
- Challenges to higher luminosity
  - Narrower beam at IP
  - Higher beam current
  - Detector works with higher beam background and trigger rates

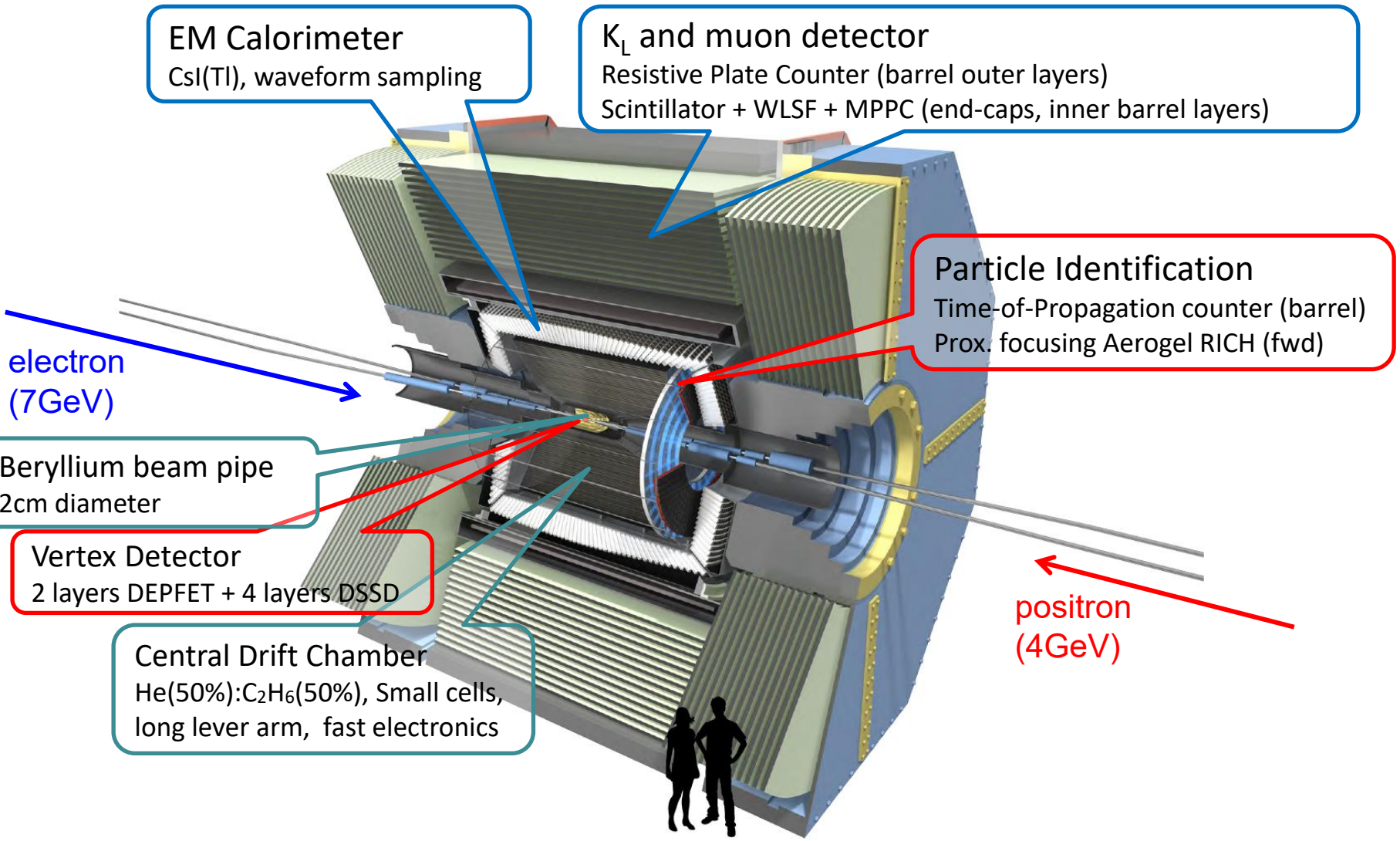
Target integrated luminosity = 50ab^{-1}
→~5x10^{10} τ pairs

  - x50 higher than previous B factory



Belle II detector

General purpose, forward/backward asymmetric acceptance

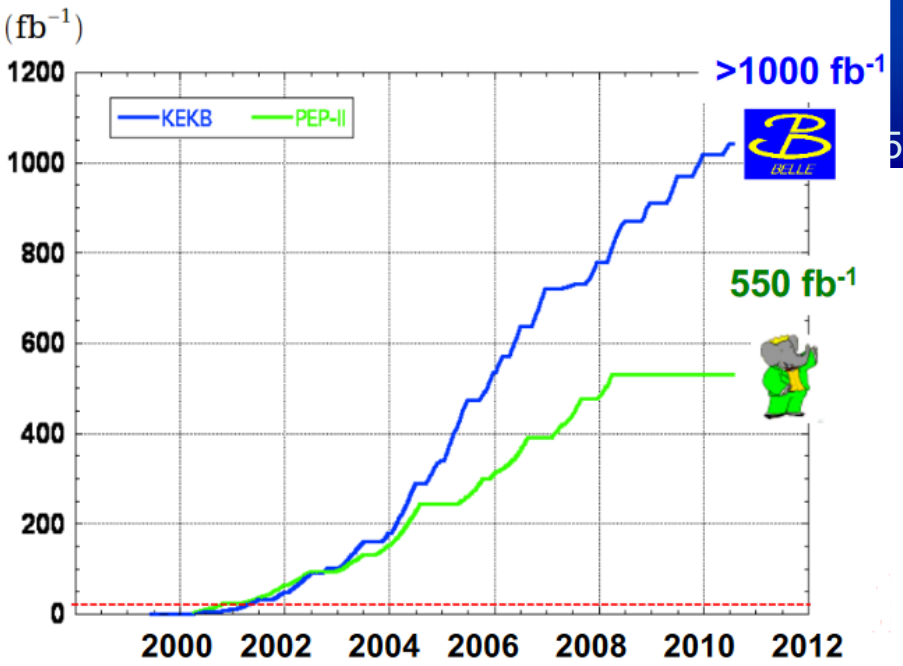


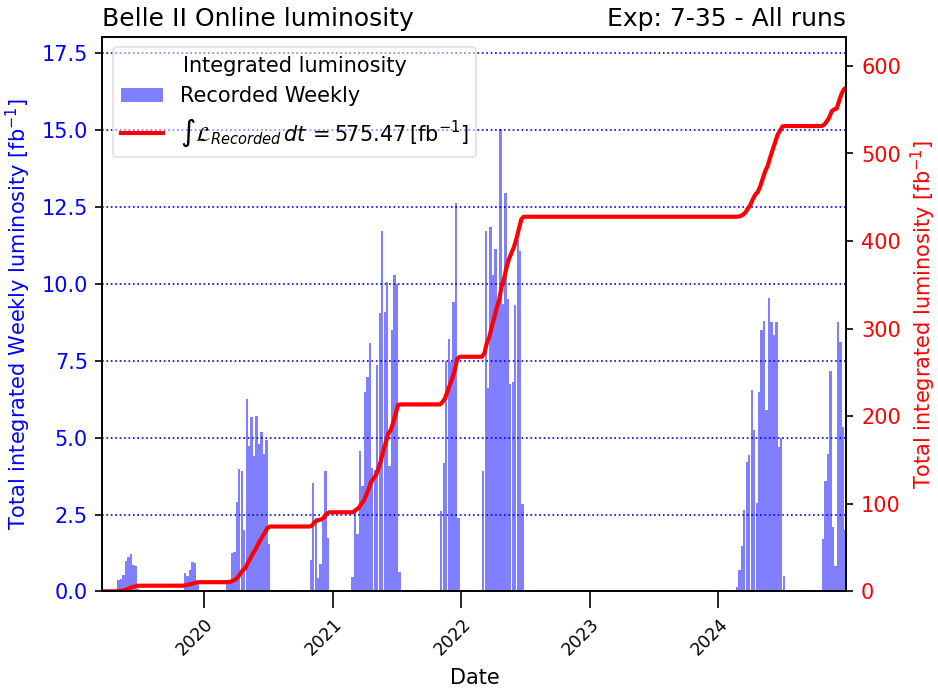
Belle/Belle II data

- Belle:
  - > 1000 fb^{-1} recorded at around Y(4S)
  - Cf. BaBar: 550 fb^{-1}
  - Peak luminosity: 2.1 x 10^{34} cm^{-2} s^{-1}

- Belle II
  - Peak instantaneous luminosity: 5.1 x 10^{34} cm^{-2} s^{-1} (world record)
  - Integrated luminosity: ~575 fb^{-1} recorded at Y(4S),
    ~42 fb^{-1} recorded 60 MeV below Y(4S), for background studies
    ~19 fb^{-1} recorded at ~10.8 GeV for exotic hadron searches

- Larger data than Belle/BaBar are coming soon.

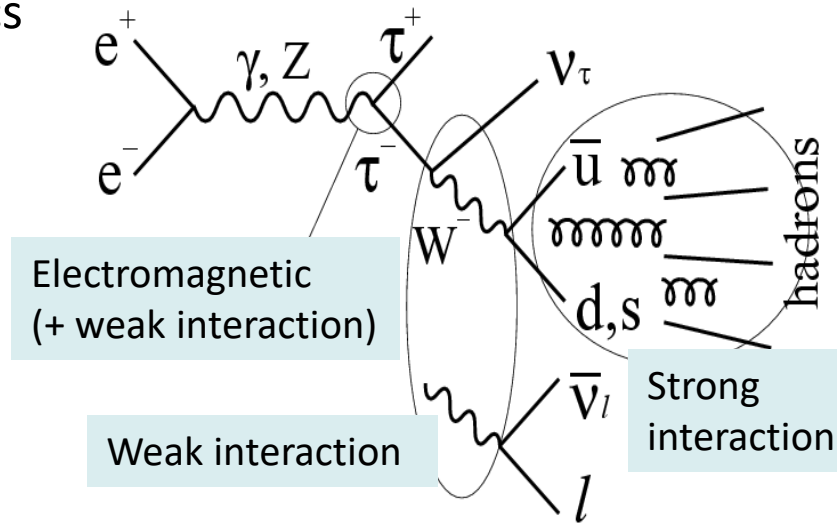




Tau physics program

- The world largest number of tau-pair events in e^+e^- collisions offer data for tau physics analyses with high precision.

- Tau mass, ν_τ mass, Lifetime
- Test of Universality
- Hadronic decays
  - Search for second class current; $\tau \to \pi\eta\nu$
  - Mass spectrum in $\tau \to \pi\pi^0\nu$
  - ...
- Electric Dipole Moment (CP/T violation)
- CP violation in tau decay; $\tau \to K_s\pi\nu$, etc.
- Lepton flavor violating decays
  - $\tau \to \mu\gamma$, $e\gamma$, $\mu\eta$, $e\eta$, $p\gamma$, $\Lambda\pi$, $\ell\ell\ell$, ..., $\ell+\alpha$

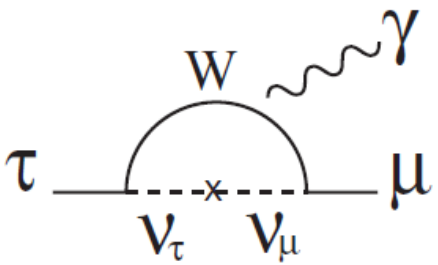


New physics interaction??

Lepton Flavor Violation in tau decay

In the Standard Model, LFV is highly suppressed.

Impossible to access; Br<O(10^{-54})

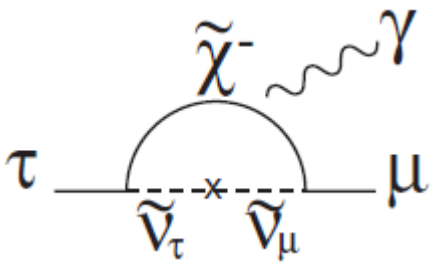


Many extensions of the SM predict LFV decays.
Their branching fractions are enhanced as high as current experimental sensitivity

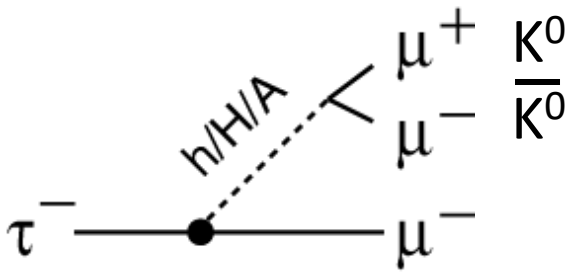
⇒Observation of LFV is a clear signature of New Physics (NP)

Tau lepton : the heaviest charged lepton

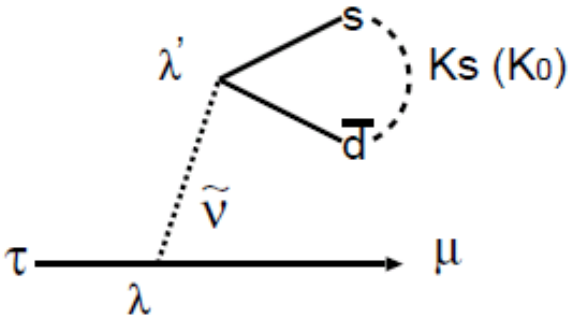
- Opens many possible LFV decay modes which depend on NP models



SUSY

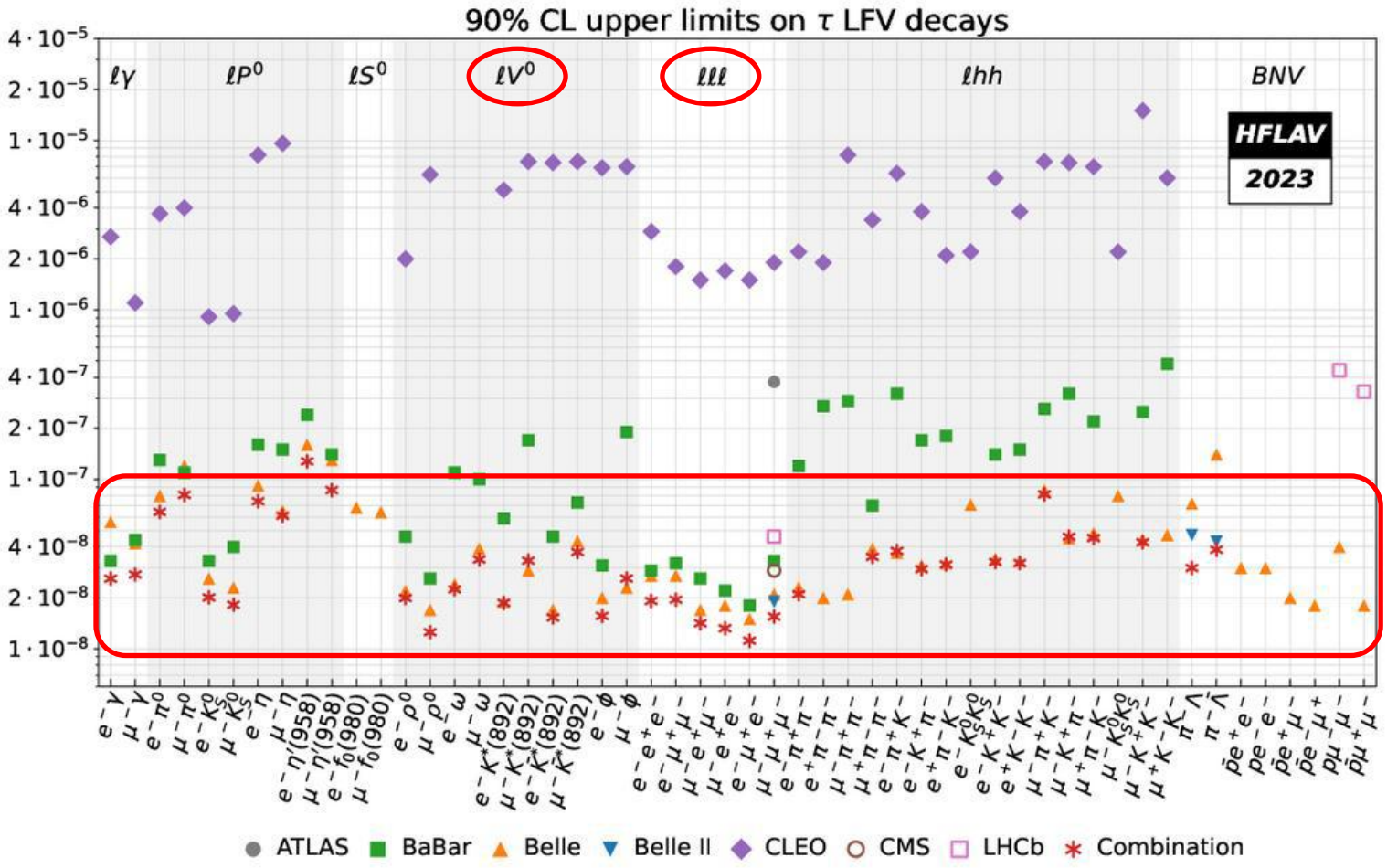


Higgs-mediation LFV



R-parity violation

Upper limits on LFV τ decays

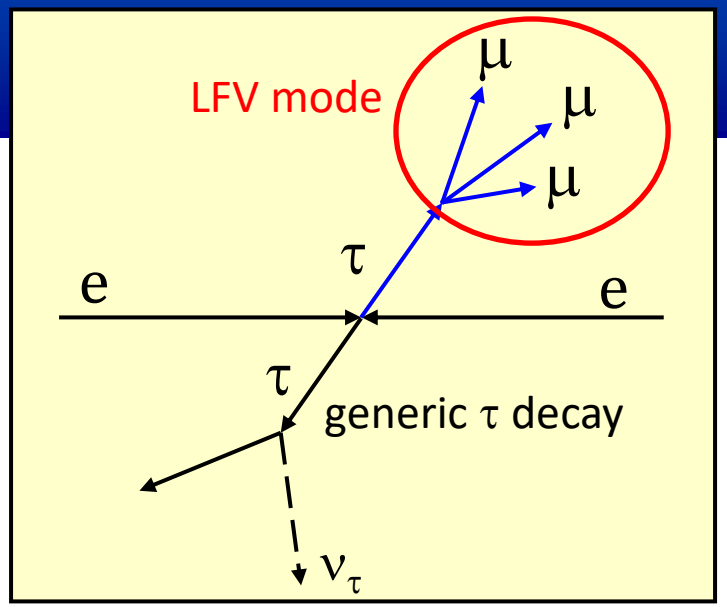


- Belle, Babar reached O(10^{-8}) branching ratio, LHCb improving the result
- $\tau \rightarrow \ell\ell\ell$, ℓ+mesons (to charged particles) show better sensitivity because of less background.

Tau LFV analysis

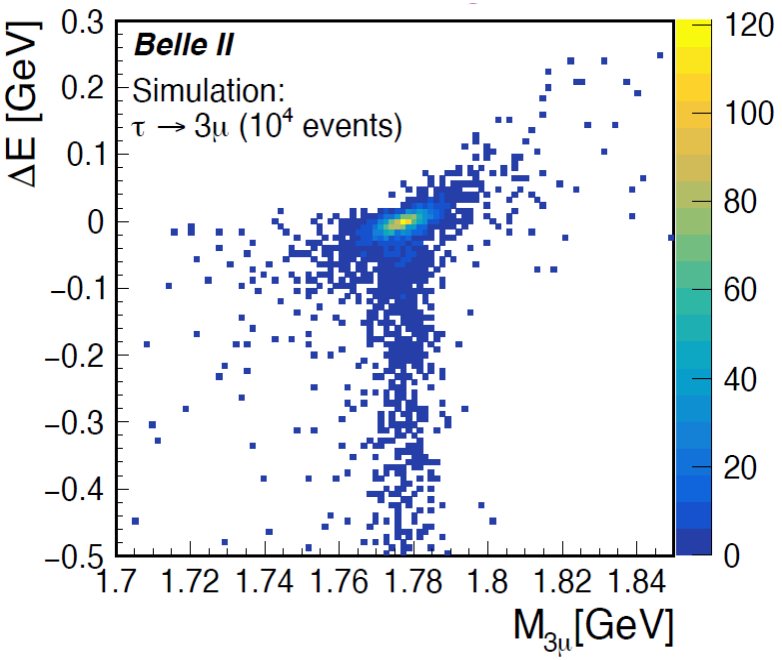
- $e^+e^- \to \tau^+\tau^-$ Br~85%
  - 1 prong + missing (tag side)
  - $\mu\mu\mu$ (LFV mode, signal side)

Fully reconstructed

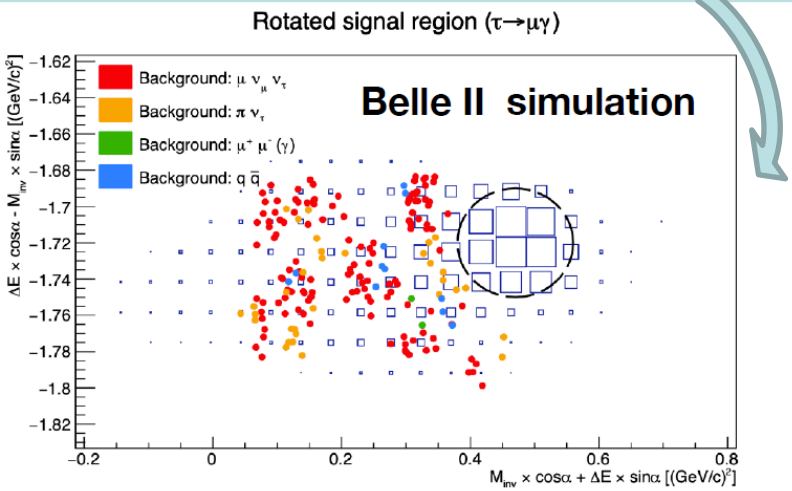


Signal extraction: $M_{3\mu}$–ΔE plane
(or rotated signal plane to reduce correlation)

Evaluate background from side band



BG contribution is small for 3lepton modes because of good PID performance, however non-negligible for ℓ+γ modes



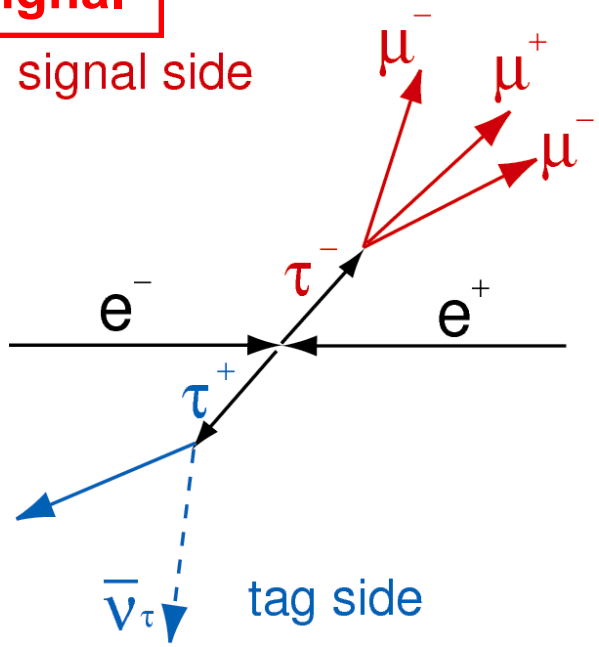
The Belle II Physics Book arXiv:1808.10567v2

LFV τ decays; Signal and Background

- $e^+e^- \rightarrow \tau^+\tau^-$
  - 1 prong tau decay (BR~85%)

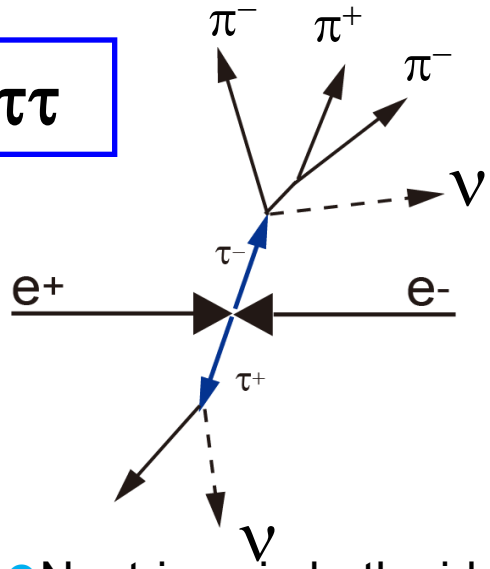
signal

signal side



- Neutrino(s) in tag side
- Particle ID
- (Mass of mesons)

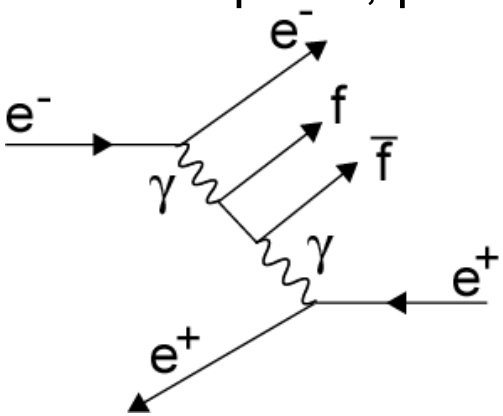
ττ



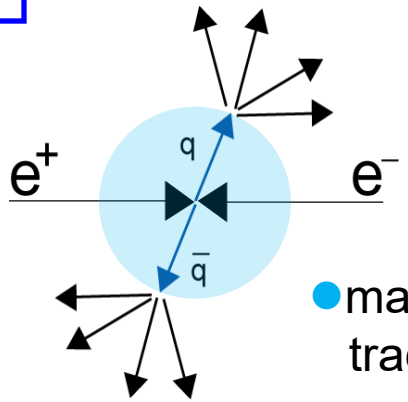
- Neutrinos in both side
- Missing energy in signal side

2photon process

f=leptons,quarks

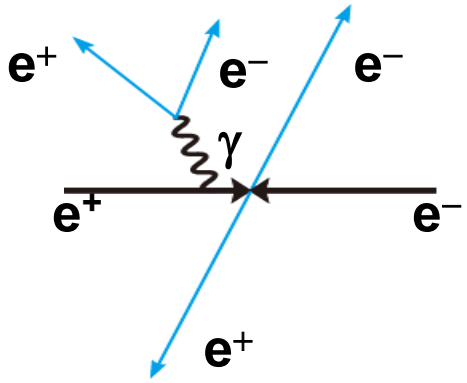


qq̄



- many tracks

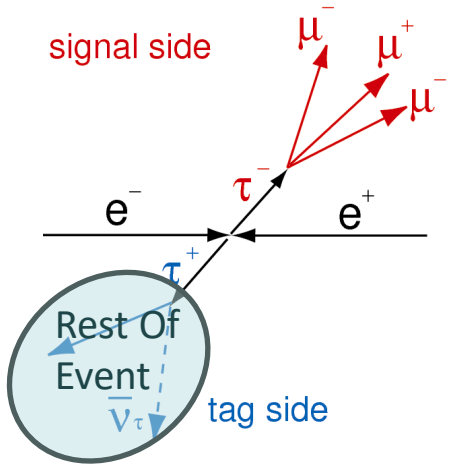
radiative Bhabha process

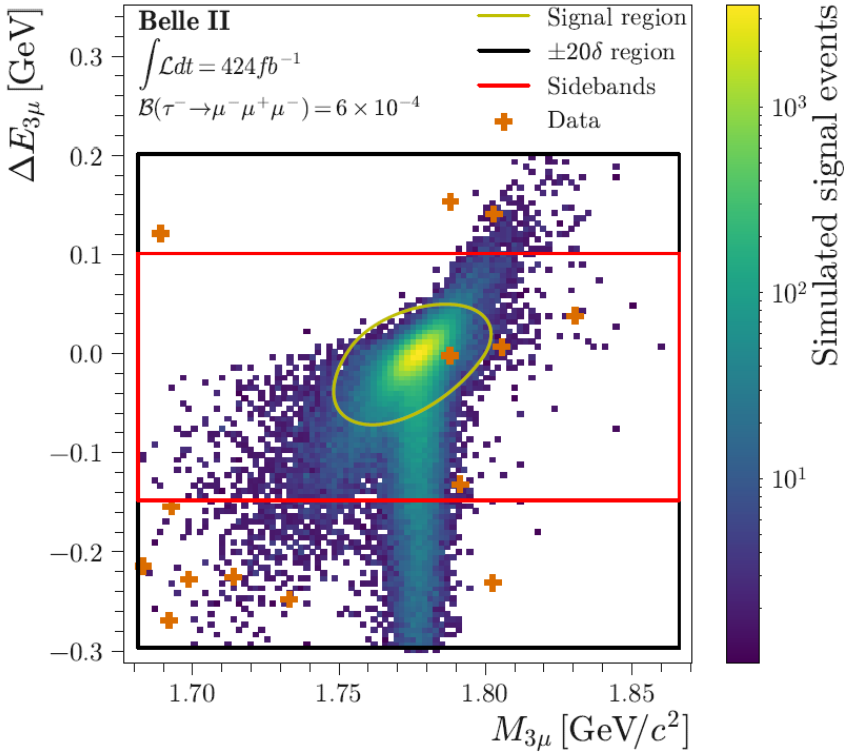


Search for $\tau \rightarrow \mu\mu\mu$

- Updated by Belle II using 424 fb^{-1} data
- Reconstruct signals with inclusive untagged approach to improve signal eff.
- Reject backgrounds with data-driven selections + Boosted Decision Tree classifier
  - Using Rest-Of-Event properties
- Signal efficiency improved
  - 20% (~3 x Belle)

- One events in the signal region
  - 0.7 events expected
- Br<1.9x10^{-8} at 90% CL
  - World's best sensitivity
  - Previous: 2.1x10^{-8} by Belle (782 fb^{-1})

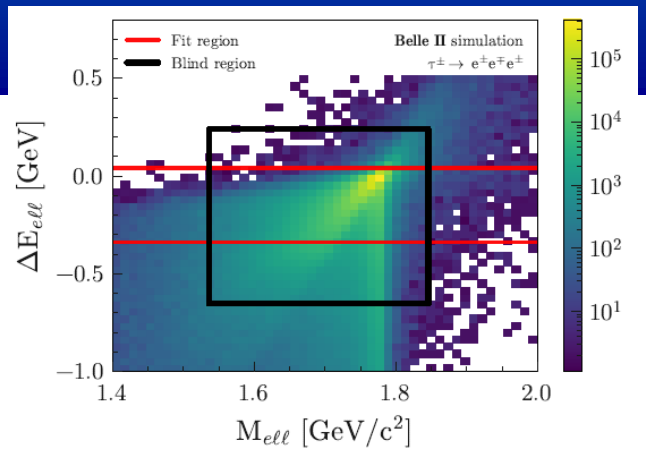


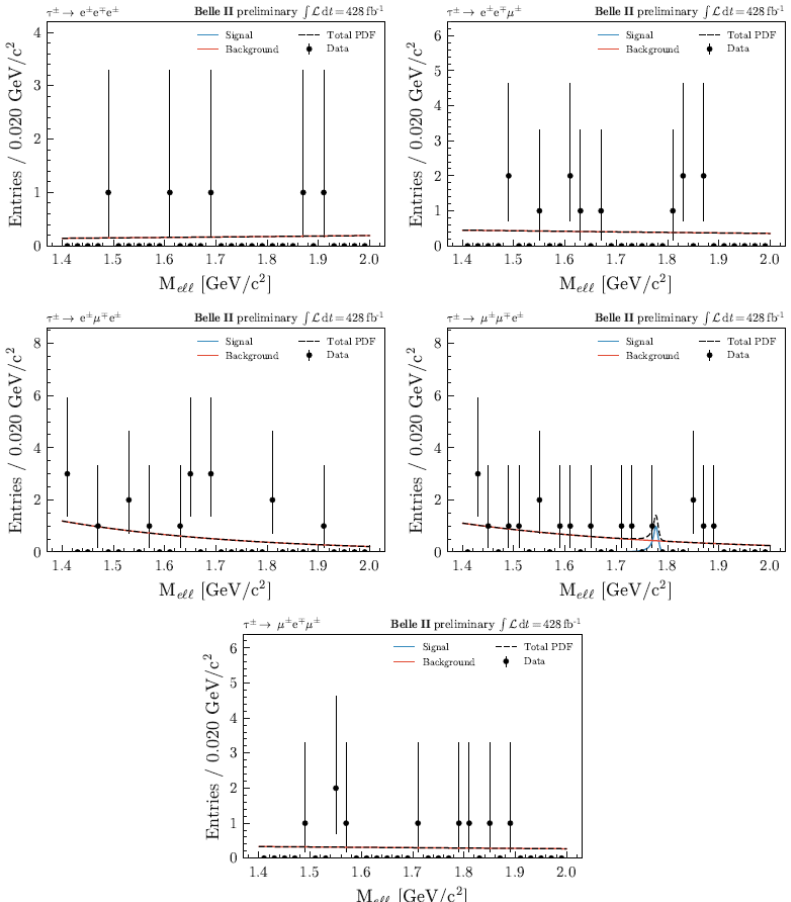


Search for $\tau \to e\ell\ell$

Belle II: [arXiv:2507.18236]

- Inclusive-tagging method
- Optimized the selection criteria for each mode
  - Cut-base preselection
  - Data-driven BDT classifier
- Signal efficiency
  - 15 ~ 24 % (2~3 x Belle)
- Applied unbinned likelihood fits to M_{ell} to improve sensitivity
- Data: 428 fb^{-1} (~3.9x10^8 $\tau\tau$) at Belle II
- No significant excess
- Br<(1.3-2.5)x10^{-8} at 90% CL.
  - Most stringent upper limit for 4 modes.

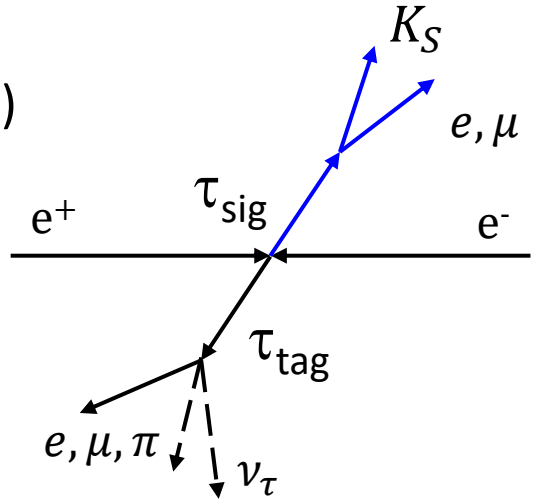


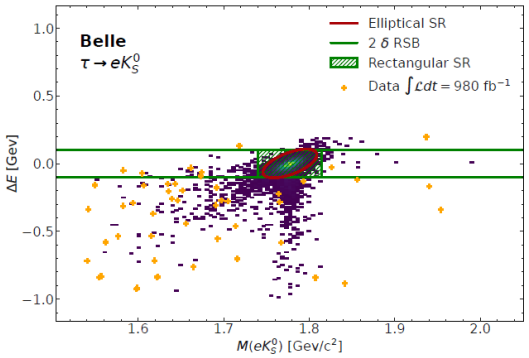


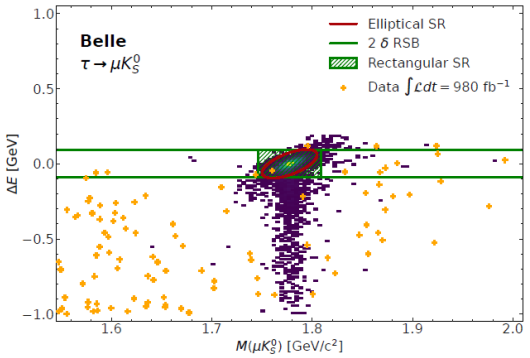
	N_{exp}	N_{obs}	C_{bg}	$\mathcal{B}$ (10^{-8})	$\mathcal{B}^{UL}_{exp}$ (10^{-8})	$\mathcal{B}^{UL}_{obs}$ (10^{-8})
$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	5	$0.52^{+2.64}_{-2.60}$	0	2.7	2.5
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	12	$-0.40^{+1.67}_{-1.68}$	0	2.1	1.6
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	17	$-2.90^{+1.48}_{-1.54}$	0	1.7	1.6
$\mu^-\mu^+e^-$	$20.7^{+6.6}_{-5.5}$	18	$-2.50^{+1.45}_{-1.52}$	$0.48^{+0.90}_{-0.48}$	1.6	2.4
$\mu^-e^+\mu^-$	$7.5^{+4.5}_{-3.2}$	9	$-0.34^{+1.93}_{-1.94}$	0	1.4	1.3

Search for $\tau \rightarrow \ell K_s$ ($K_s \rightarrow \pi^+\pi^-$)

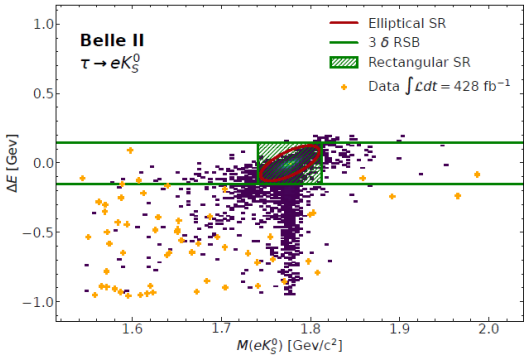
- Combined data set of Belle (980 fb^{-1}) + Belle II (428 fb^{-1}) = 1408 fb^{-1} (1.3×10^9 $\tau\tau$)
- One-prong tag approach
- Main BG is low-multiplicity QED process for eKs and $e^+e^- \rightarrow qq$ for μKs
- Optimized selection for each signal and tag mode
  - For Belle and Belle II separately
  - Data-driven selections + BDT
- Signal eff.: ~10% for all cases

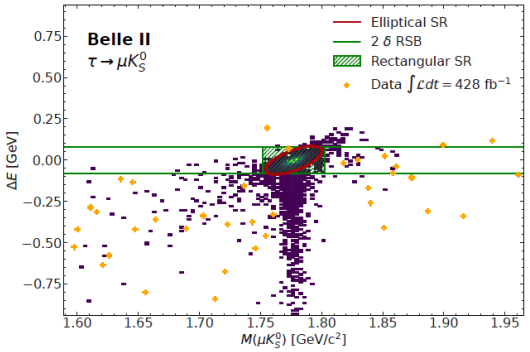






- Observed 0 event for eKs and 1 event for μKs
- Br< 0.8×10^{-8} and 1.2×10^{-8} at 90% CL
  - Most stringent upper limits

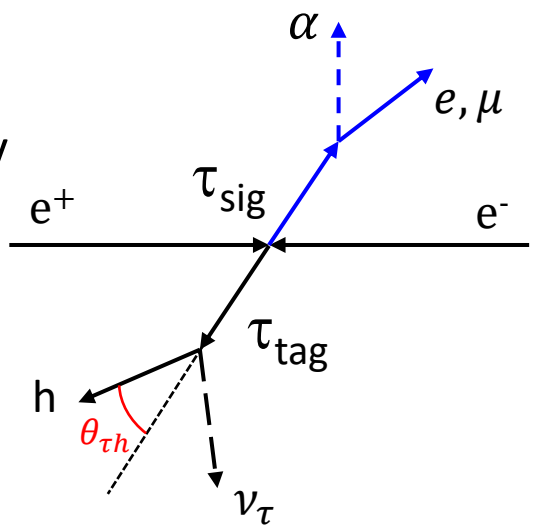




LFV $\tau \to \ell\alpha$ search

Belle II: [PRL 130 (2023) 181803]
Belle: [arXiv:2503.22195] New!

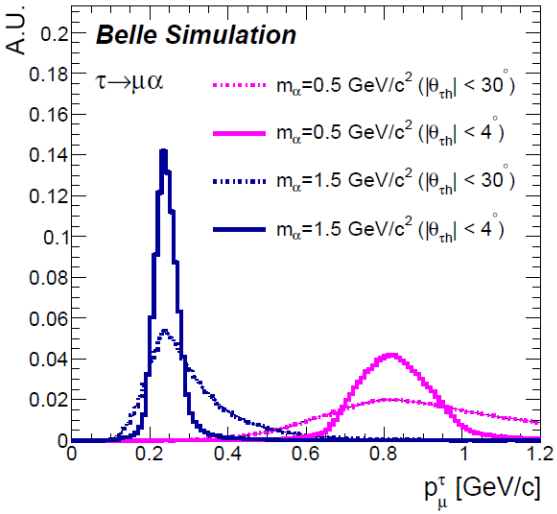
- Search for LFV two-body decay $\tau \to \ell\alpha$ (ℓ=e,μ)
  α is an invisible gauge boson that can be predicted by several new-physics models; LFV Z', light ALP, etc.



- Lepton momentum in signal side is monochromatic at τ_{sig} rest flame, while broad distribution of background $\tau \to \ell\nu\nu$ decays.
  - Use p_ℓ^τ for the signal extraction
  - Need tau flight direction to calculate
    - Use hadron direction in tag side as the tau direction
- Calculate the angle between hadron and primary tau direction, by using hadron momentum/energy.

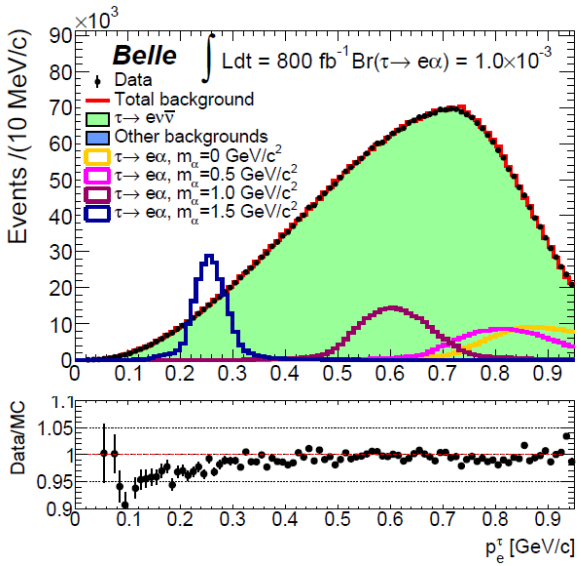
$$\theta_{\tau h} = \arccos\left(\frac{|\vec{p}^{\,\mathrm{c.m.}}_{\tau_{\mathrm{tag}}}|^2 + |\vec{p}^{\,\mathrm{c.m.}}_{h_{\mathrm{tag}}}|^2 - (\sqrt{s}/2 - E^{\mathrm{c.m.}}_{h_{\mathrm{tag}}})^2}{2|\vec{p}^{\,\mathrm{c.m.}}_{\tau_{\mathrm{tag}}}||\vec{p}^{\,\mathrm{c.m.}}_{h_{\mathrm{tag}}}|}\right)$$

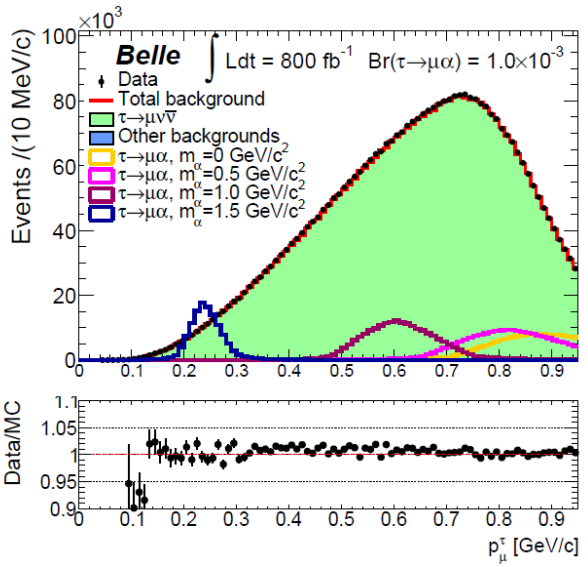
- By requiring a selection on $\theta_{\tau h}$, we can improve p_ℓ^τ resolution.

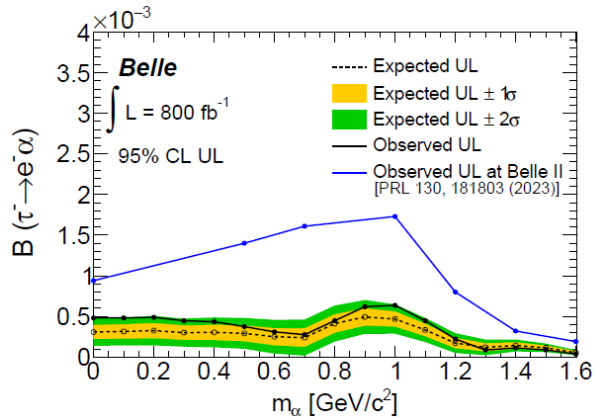


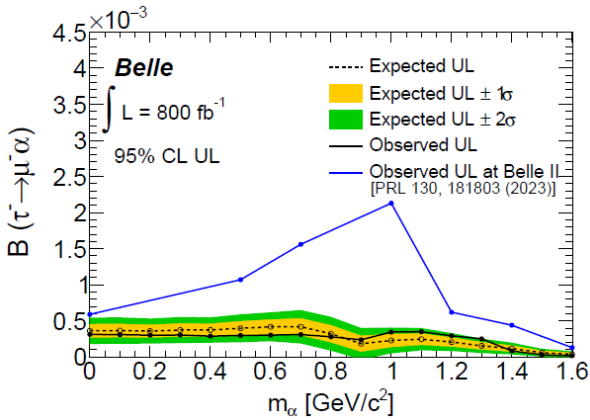
LFV $\tau \to \ell\alpha$ search

- Two-body signal decay will appear as a bump on the three-body $\tau \to \ell\nu\nu$ decay in the p_ℓ^τ distribution.
- Selection criteria are independent of α mass.
  - Detection efficiencies are 0.3–1.5% depending on α mass
- No bump seen using 7.4×10^8 tau pairs by Belle
- Set 95% C.L. upper limits
  - Most stringent limit





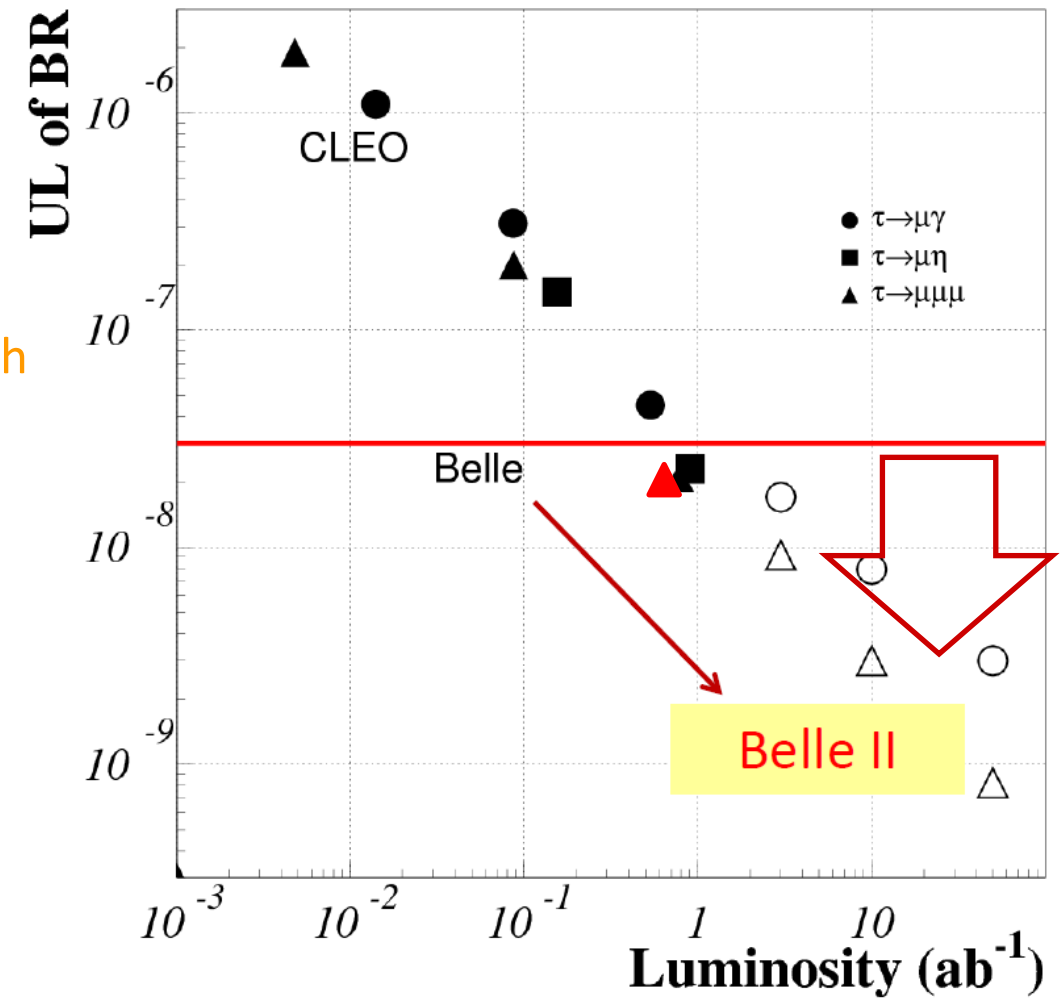




Prospects at Belle II

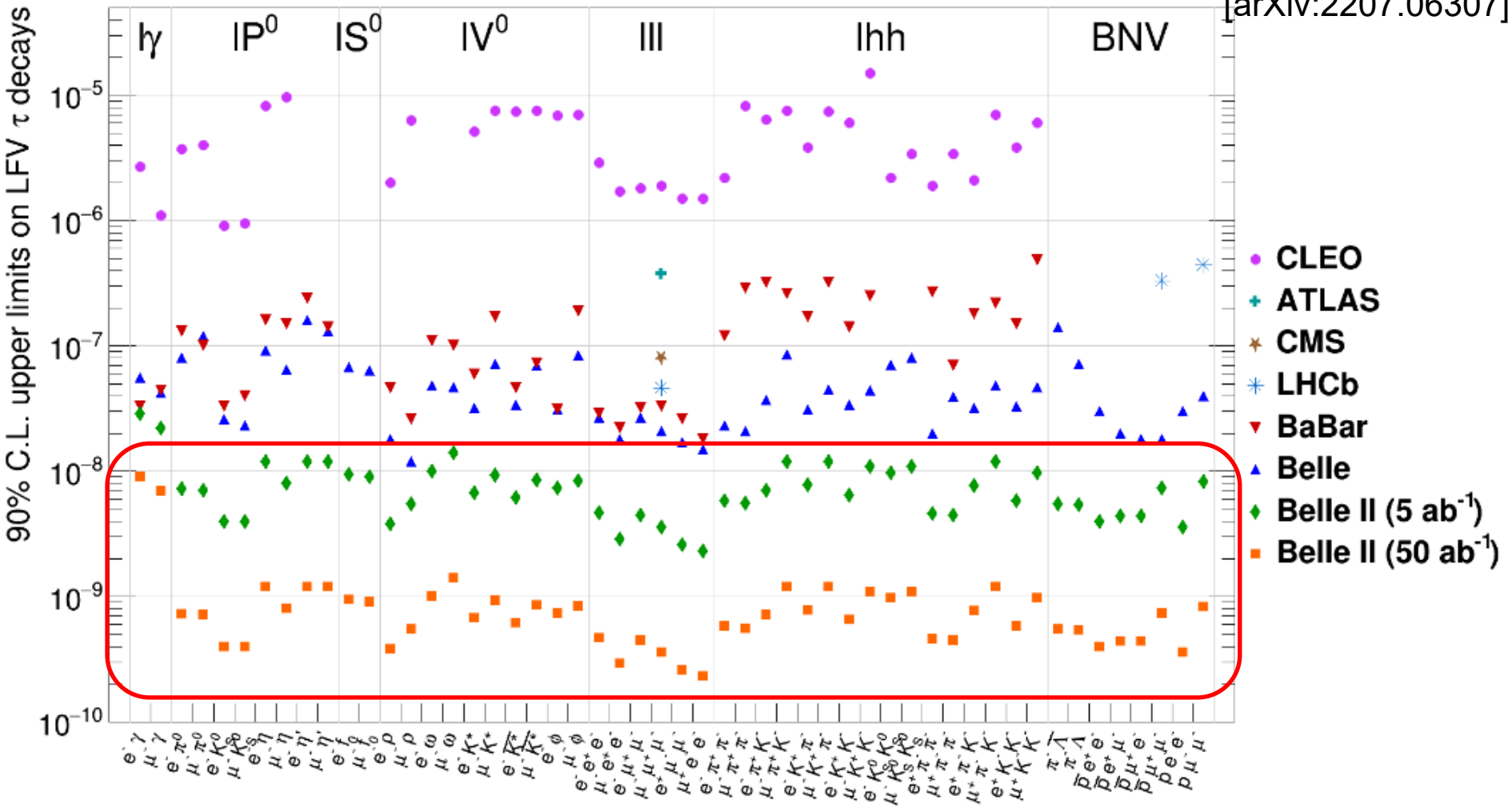
- Will collect 50ab^{-1} data, with upgrading detector and accelerator
- B($\tau \rightarrow \mu\mu\mu$)~O($10^{-10}$) at ~50ab^{-1}

- Background suppression with high signal efficiency is key issue.
  - Understanding of background (beam BG, fake PID etc.)
    → Improvement of reconstruction algorisms
  - Intelligent event selection by machine learning technique



Prospects at Belle II

[arXiv:2207.06307]



- Estimates assuming the background level scaled by luminosity
  - Recent analyses have already improved the S/N.
- Belle II will push the sensitivity down to $O(10^{-9 \to 10})$ at 5 → 50 ab^{-1}

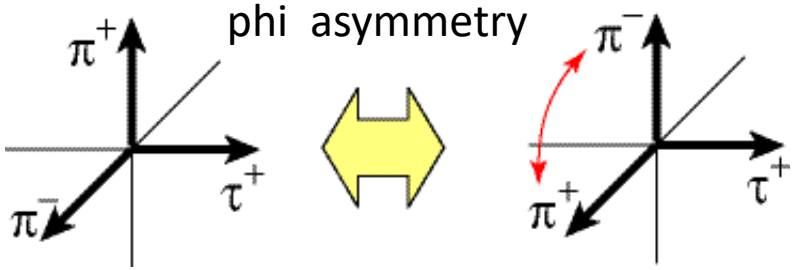
Summary

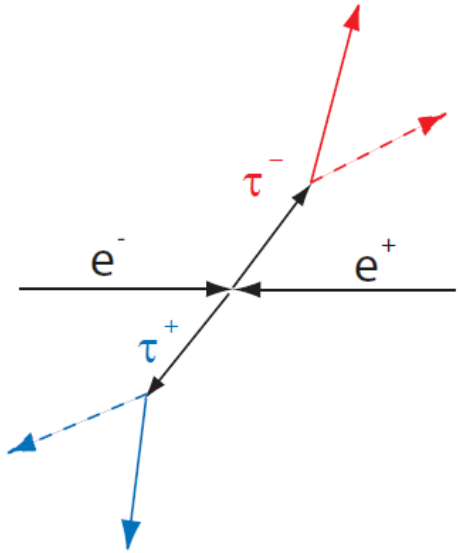
- Belle / Belle II experiments are producing more results on tau LFV searches.
  - Achieving the branching ratio sensitivity of 1×10^{-8} for $\tau \rightarrow \ell\,\ell\,\ell$, ℓKs
  - Improved sensitivity of $\tau \rightarrow \ell\alpha$ search
  - New results using improved detector understandings and intelligent analysis with machine-learning techniques.
- Belle II experiment
  - Achieved world record peak luminosity; $L = 5.1\times10^{34}\ cm^{-2}\ s^{-1}$
  - Accelerator tuning is in progress, and more data will be recorded.
- Belle II will collect ~5×10^{10} τ pairs
  - Tau LFV searches will reach the higher sensitivity compared to the previous experiments
    - The background free modes, such as $\tau \rightarrow$ 3 leptons, can be reached to $O(10^{-10})$ branching ratio sensitivity.
  - We can perform more precise analysis also on B-meson decays, tau hadronic decays, CPV/EDM, b/c-hadron resonances etc.

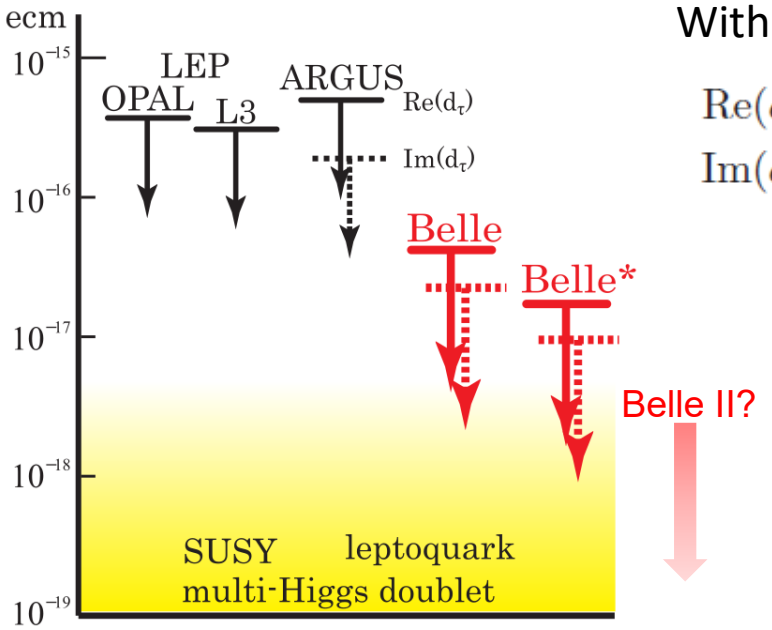
Electric dipole moment of τ lepton

- CP violating decay angular distribution

$$\mathcal{L}_{\text{eff}} = \bar{\psi}(i\,\partial\!\!\!/ - eQ\,A\!\!\!/)\psi \; - \frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi d_\tau F_{\mu\nu}$$







With Belle's 833 fb^{-1} data (~7.6x10^8 τ pairs)

$$\text{Re}(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17}\ e\text{cm},$$
$$\text{Im}(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17}\ e\text{cm}.$$

at 95% C.L.

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Sensitivity of O(10^{-19}) *e*cm can be achievable in near future, by improving analysis method.